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THE WELDABILITY ASSESSMENT OF THERMALLY HARDENED S540Q STEEL SHEETS

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Abstract

High strength thermally hardened steels are more difficult to weld than low carbon construction steels. There is a danger of cold cracking caused by the presence of martensite in welded joints. The thermally hardened 12 mm sheets of S540Q steel underwent research. The sheets were welded semi-automatically by MAG method, in the welding conditions usually applied in industry for welding normalized sheets of this steel. The welding technology was presented. The X-ray tests were performer, which confirmed the achievement of metallically continuous joints. Samples were taken from the joints and the joints hardness distribution measurements were conducted. The microstructure was examined and the static tensile tests as well as technological bend tests were carried out. Hardness measurements were performed in three measurement lines for each joint according to PN-EN 1043-1:2000 requirements. Joints microstructures were examined in the joints axis, in HAZ and in native materials. Steel microstructures were classified as low carbon tempered matrensite of layered construction. Mean values of the selected joints tensile strengths were also presented. The tensile tests values of native materials of metallurgic certificates were given for the sake of comparison. The research results presented in the paper made it possible to determine the weldability of S540Q steel.

Keywords: *low-alloyed quality steels, heat treatment of S540Q steel, welded constructions*

1. Introduction

Unalloyed steels containing micro additives were introduced to industry as steels to be applied without thermal treatment. The micro additives were responsible for the increase of steel properties by disintegrating grain and hardening the ferrite. However, the increase of hardness and ductility of these steels was still not satisfactory. In order to make up this deficiency proper heat treatment was applied. First, the so-called normalization was used and then heat hardening was utilized. As a result, weldable steels of elevated and high strength were obtained. Such steels allow applying higher static loads or to lower the construction mass. It is believed that high strength thermally hardened steels are more difficult to weld than low carbon construction steels. There is a danger of cold cracking caused by the presence of martensite in welded joints. The decrease of ductility can occur in the heat impact zone. A bainitic structure, which influences the decrease of ductility, can be formed uncontrollably when welding with too high linear force. Therefore, the welding process should be carried out with utmost care so as not to induce these unfavourable phenomena [3]. High strength thermally hardened weldable steels are quality steels with micro additives that disintegrate grain and that underwent thermal hardening (thermal improvement). This treatment consists in steel sheets hardening on quenching press with double-sided water spray within the temperature range of 900-950°C. Sheets tempering is performed in the temperature of 600-700 ºC with cooling in the air. After this, heat treatment sheets gain the structure of tempered layered martensite with carbide and cyanide disperse separations in some bainite steels [2, 9]. Steel hardening can also be conducted straight on rollers from the temperature of the rolling finish [1, 4]. It allows reaching desired plasticity border in the steel with lower carbon equivalent C_e, and consequently better weldability than in steel hardened after re-heating [7]. It is assumed that thermal hardening can lead to the decrease of weldability. Therefore, it seems reasonable to perform thermal hardening straight on rollers. The research was undertaken in order to explain and determine whether the thermal hardening enables the achievement of high strength weldable joints, which show satisfactory weldability at the same time.

2. Research

Thermally hardened 12 mm thick S540Q steel sheets were subjected to research. Tab. 1 presents chemical constitution of an examined steel sheet.

Tab. 1. Chemical constitution of the sheet examined according to metallurgic certificates.

Steel sign	Chemical constitution, % of mass											
	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	V	Nb	Al.
1	2	3	4	5	6	7	8	9	10	11	12	13
S540Q	0.18	1.36	0.32	0.020	0.016	0.02	0.01	0.02	-	0.01	0.035	0.04

Welding was performed by semi-automatic MAG method. The filler metal, scheme as well as the welding parameters used in the research were identical to the ones used in paper [5]. The butt joints were welded without preheating, at the interlayer temperature of 100°C in a lower position.

They were welded semi-automatically in the shield of 80% Ar and 20% CO_2 mixture, on a copper plate, in Y welds. The preparation of sheets segments edges and the number and sequence of weld runs is shown in Fig. 1.

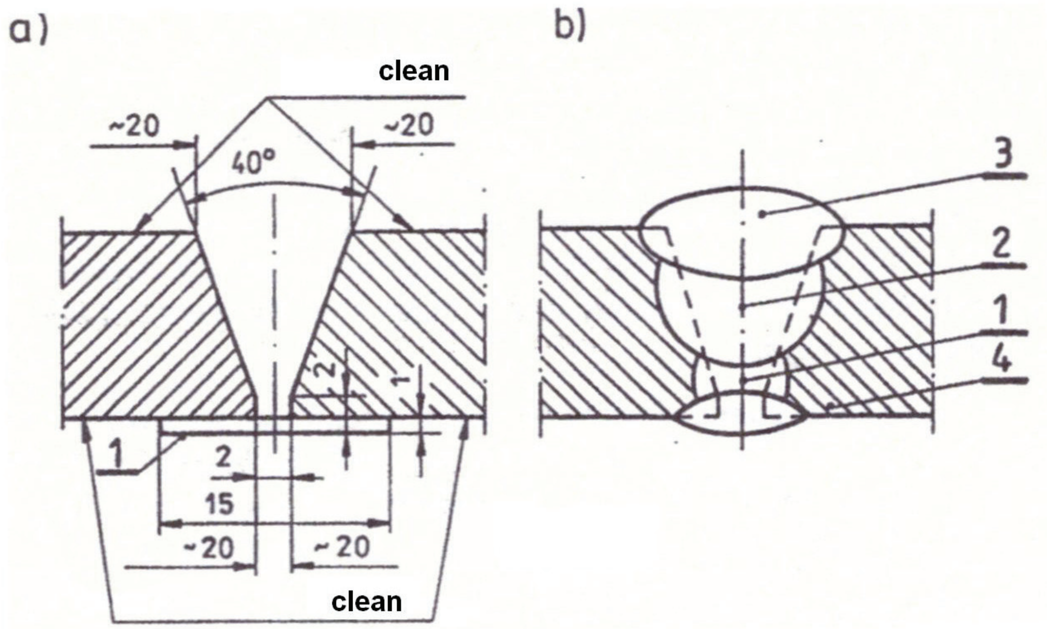

Fig. 1. The diagram of butt weld joints a) edges preparation, 1- copper plate, b)- sequence of weld runs, 1- weld run, 2 – weld axis, 3- filler runs, 4- root run

The achievement of metallically continuous joints was recognized by X-ray examination. The correctness of making test joints was proved by the measurement of transverse warp and edges of sample sections. However, in order to assess the usefulness, samples were taken from test joints, the hardness distribution measurements were taken in the joints and the microstructure was examined. Moreover, static tensile tests and technological bend tests were carried out.

Hardness measurements were performed in three measurement lines for each joint according to PN-EN 1043-1:2000 requirements. Fig. 2 shows the location of hardness distribution measurements lines in butt-welded joints.

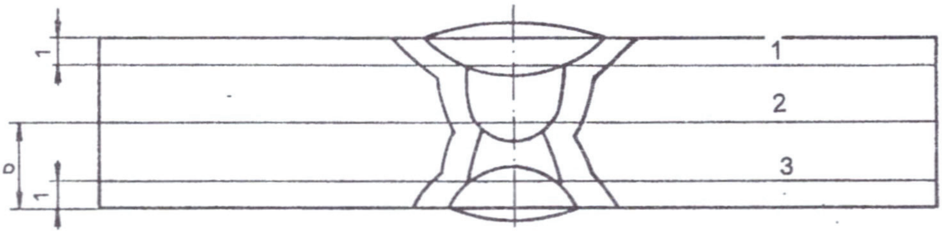

Fig. 2. The location of hardness distribution measurements lines in butt-welded joints, 1- back of weld, 2 - centre, 3 - midpoint

The diagram of hardness distribution in a joint was shown in Fig. 3. The characteristic hardness values in a welded joint are presented in Tab. 3.

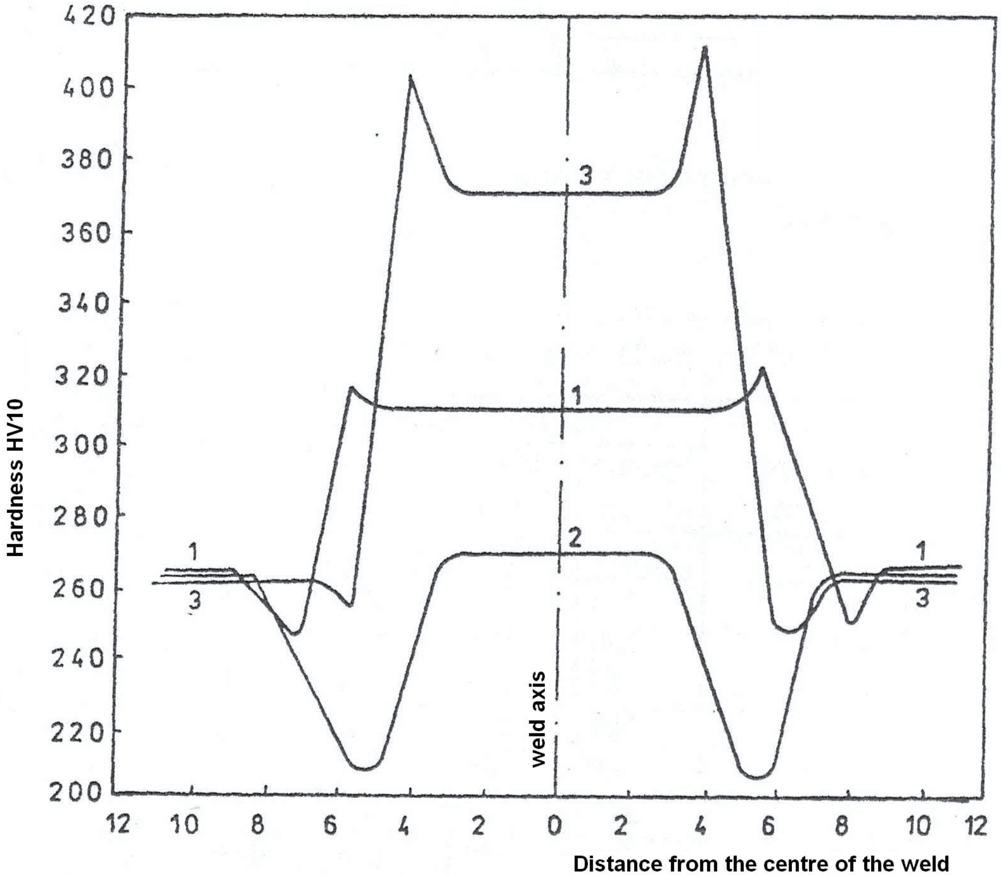

Fig. 3. HV10 hardness distribution in a welded joint of S5400Q steel sheet

The joints microstructure was examined in the weld axis, in HAZ and in native materials with the use of Neophot-2 optical microscope. Steel microstructures were classified as low-carbon tempered martensite of layered construction. Microstructure differences in particular joints zones were the most clear in the observation lines 1 mm distance from the sheet joints surface. These included dendritic joint structures - typical for welded joints, grown grains in overheating zone, fine-grained normalized zone and partial transformation zone at the HAZ entrance to native material. No metal discontinuities in joints were found.

Tab. 2. Hardness in welded joint of S540Q steel

Steel sign	Joint measurement line	HV hardness				AHV10max	
		Weld	Min HAZ	Max HAZ	Native material	HV10	%
1	2	3	4	5	6	7	8
S540Q	back of weld	273	193	283	200	83	41.5
	centre	286	183	294	191	103	53.9
	root of weld	35	199	394	200	194	97.0

The joints tensile tests were carried out on samples presented in Fig. 4. The mean values of the selected joints tensile strengths are shown in Tab. 3. The table also contains the tensile strengths of native materials given in metallurgic certificates for the sake of comparison.

Tab. 3. Mechanical properties of S540Q steel

Steel sign	Samples	YS MPa	UTS MPa	EL %	YS/UTS	UTS_w/UTS_m
1	2	3	4	5	6	7
S540Q	native material	545	630	23.5	0.865	-
	welded joint	-	652	-	-	1.03

The bend tests were conducted by means of bending arbour of 36 mm in diameter. The cracks on the lengthened surfaces of samples that exceeded the dimensions by 3 mm in any direction did not appear while lengthening from the back of weld and from the root of weld at the bend angle of 180°.

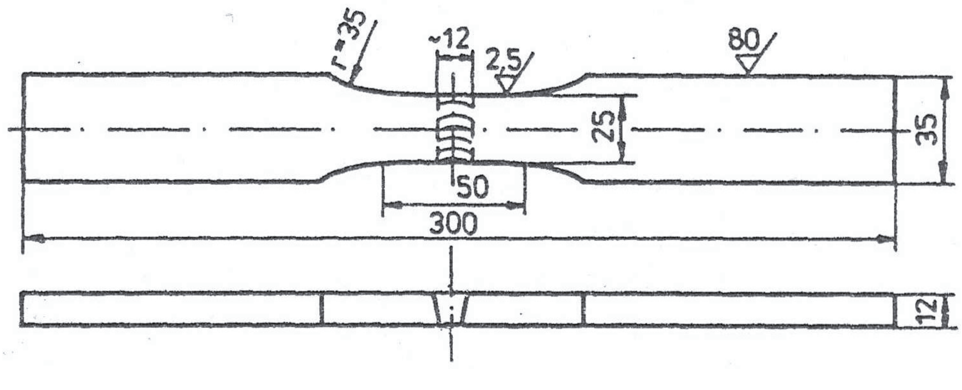

Fig. 4. The sample for the tensile test of welded joint with cut excess weld metal

3. Discussion on the research results

X-ray radiographic and metallographic examinations showed that the welds obtained were metallically continuous, so the basic condition of recognising the sheets examined as weldable was met. However, in case of joints applicability the DnV regulations [6] state that the tensile strength of butt weld joints with cut excess weld metal, located across the sample lengthening direction should not be worse than tensile strength of native material. The results of tensile tests presented in Table 3 show that this condition was also satisfied in the applied welding conditions.

It is worth mentioning that the occurrence of cold cracks in the joints depends on the following conditions: the chemical composition of steel and weld, the amount of heat and hydrogen introduced during welding, the speed of joints cooling and the values of the remaining stresses [3].

If the joint cooling speed after welding is too high, the excessive hardening can occur in the HAZ. On this account, it is possible to assume that the joint maximum hardness is a sure measure of sheets weldability in given welding conditions. Sheets weldability will be better if the HAZ hardness is lower.

As seen in Tab. 4, the joints tensile strength was not lower than the strength of native material. High border of native material plasticity is notable, and constitutes 0.865 of its tensile strength. Therefore, it seems worthwhile to increase the safety coefficients when determining permissible sheets stresses in constructions.

In the welds examined, the lowest SWC hardness increase was observed in the measurements line in the centre of joints thickness. This zone was formed during setting the first weld layer and was tempered by heat introduced when setting the second layer of welds. Hence, the considerable drop of HV_{max} hardness in the SWC area.

For the purpose of weldability assessment in the paper [8], the following 5 grades were assumed based on maximum HAZ hardness of welded joints:

- grade 0 for $HV_{max} = 110 – 280$,
- grade 1 for $HV_{max} = 281 – 340$,
- grade 2 for $HV_{max} = 341 – 400$,
- grade 3 for $HV_{max} = 401 – 460$,
- grade 4 for $HV_{max} > 460$.

Taking into account the above criteria and HAZ hardness measurements results in line from the root of weld, where HV_{max} was the highest, it is possible to assign welding grades to the sheets examined, that is grade 2 for S540Q steel sheet. However, if the mean HV_{max} value of three measurement lines were assumed – the sheets examined would reach grade 1. It is also worth noticing that the biggest HAZ hardness occurs in measurement line from the root of weld, where the highest weld cooling speed was observed. Modification of the conditions of welding sequence in order to decrease the cooling speed of this run makes it possible to reduce HV_{max} in the joints.
In case of butt weld joints, no cracks appeared at bending to the angle of 180°.

DnV regulations [6] require the welded joints not to show cracks bigger than 3 mm in any direction when being bent to an angle of 180°, however lower bending angles are permitted for welded joints of steel having E 420-690 hardness category. And so when accepting a weld, DnV regulations [6] as well as PRS regulations [1] require performing weld bend tests only to an angle of 120°.

In the view of the results obtained from bend tests it can be stated that a good plasticity was observed.

4. Summary

X-ray and metallographic examinations have shown that the welding technology applied allowed to produce a joint of satisfactory weldability.

The highest HAZ hardness appears in the measurement line at the root of weld, where the highest weld cooling speed was occurred. Modification of the conditions of welding sequence in order to decrease the cooling speed of this run makes it possible to reduce HV_{max} in the joints.

Welded joints tensile test showed that their tensile strength is not lower than that of the native material.

Bend tests showed no cracks, when they bending to the angle of 180° and so the S540Q steel meets the requirements of the classification societies.

It is possible to obtain a S540Q steel welded joint of good weldability while welding by means of MAG method without any extra activities, which could improve the weldability.

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